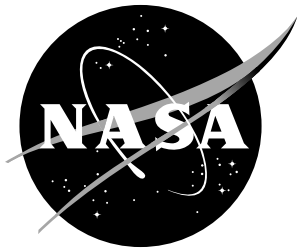


Utility Aspects of Space Power: Load Management Versus Source Management

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TECHNICAL MEMORANDUM

UTILITY ASPECTS OF SPACE POWER: LOAD MANAGEMENT VERSUS SOURCE MANAGEMENT

INTRODUCTION

Electrical power, as an area of study, is relatively young as compared to language, chemistry, physics, mathematics, philosophy, metallurgy, textiles, transportation, or farming. Practically all of the technology that has enabled the huge, continent-spanning power grids that have become ubiquitous in developed countries was developed in the last 150 years. In fact, Tesla's advocacy of alternating current (ac) for transmission just won out in the beginning of this century. Despite the novelty of the field as a whole, space power applications are, of course, much newer. This report will look at the history of space power and compare it to its older sibling on Earth, forming a basis for determining appropriate transitions of technology from the terrestrial realm to space applications.

AN HISTORICAL LOOK AT SPACE POWER CONTROL

To date, most space power systems have been minutely designed for the loads they are intended to support. As satellites grow in complexity, however, effective use of available resources requires the ability to have different modes of operation that use loads in different combinations. The power systems must be designed and operated so that the needs are met in every combination. As long as the loads are known in advance, all of the possible modes can be specifically designed for, even for significantly complex vehicles. In cases where loads will be changing in ways that are a priori unknown, though, the power system takes on aspects of a utility; load and source must be matched on the fly.

This section looks at some of the history of space power. Attention is focused on satellites, as opposed to launch vehicles, because of their longer lifetime.

Spacecraft Power Designs

The first satellite put into orbit by humans was *Sputnik I*. It was powered by chemical batteries, which kept the transmitters broadcasting for a little over 3 weeks.¹ *Explorer I*, the first U.S. orbiter, was similarly battery powered. *Vanguard I*, launched in early 1958, was the first satellite to carry solar cells coupled with secondary batteries to supply vehicle power. This configuration, called a photovoltaic system, has become the pattern for most satellites in Earth orbit, both low-Earth orbit and higher orbits, such as geosynchronous orbit.

Photovoltaic systems are also the most common choice for spacecraft intended to travel inside the orbit of Earth, such as the *Magellan* probe to Venus. Probes traveling to the outer planets (further from the Sun than Earth) are less well suited to photovoltaics because of the lower solar flux. An object which is twice as far away from the Sun as Earth is only gets 25 percent of the solar

radiation. The most common solution has been to use radioisotopic thermal generators (RTG's). RTG's use the heat generated by decaying radioisotopes (usually plutonium-238) to generate electrical energy through thermocouples. RTG's are heavy and expensive compared to a photovoltaic system for Earth orbit, but they do provide a small, dependable amount of power. The amount of energy they produce drops according to the half-life of the fissionable. Having a radiation source on the vehicle can be a problem for some instruments, at least requiring special design or shielding. There are currently questions as to fuel availability and willingness to allow launches of the fissionable materials for future missions.

Several other ideas for power sources have been suggested. The Soviet Union flew several Topaz nuclear reactors. In the U.S., the SP-100 program presented a design for a space nuclear reactor. Solar dynamic power, focusing solar energy into a heat reservoir and using a heat engine for generation, is nearing the prototype stage.

The following are some short looks at several different spacecraft and their power systems, generally increasing in size and complexity.

Sputnik I. *Sputnik I* (or 1957 Alpha) (fig. 1), was launched on October 4, 1957. Chemical batteries powered the instruments and two transmitters. The transmitters ceased broadcasting on October 27, 1957; reentry was on January 4, 1958.¹ This represents the simplest sort of “disposable” satellite; batteries capable of supplying a few watts of power were sized for (and probably defined) the life expectancy of the spacecraft.

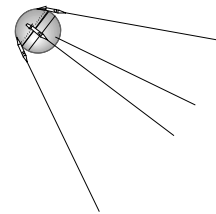


Figure 1. *Sputnik I.*

Voyager I. *Voyager I* (fig. 2) was launched September 5, 1977, on a mission that took it to Jupiter and Saturn and outward toward the edge of the solar system. The source for the power system is three RTG's. At launch, the three RTG's had a power output of 475 W. The science experiments need between 210 and 220 W to operate. The power output is expected to fall to that level in about 2015.² As with *Sputnik I*, electrical power is the life limiting factor in spacecraft use. Before the power level is too low to keep the vehicle alive, *Voyager I* will be more than 100 times the distance from the Sun to the Earth;³ at this distance, a solar array would have to have 10,000 (that is 100^2 , due to the inverse square law for solar radiation) times the area as in Earth orbit to collect the same energy.

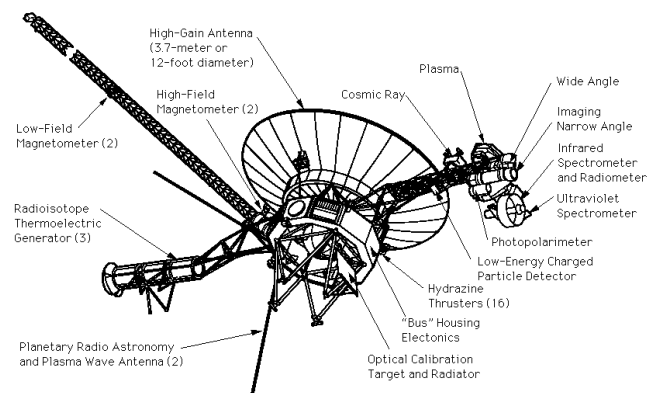


Figure 2. *Voyager I.*

Power management on *Voyager I* consists of not using more than the power available. Since there is no energy storage, management does not have to involve a time component; it just needs to be within limits at each point. The power can either be used or dissipated as heat.

The Advanced X-ray Astrophysics Facility–Imaging. The *Advanced X-ray Astrophysics Facility–Imaging* (AXAF-I) (fig. 3) is the latest of the Great Observatory series of satellites. As

the *Hubble Space Telescope (HST)* is for visible light, so *AXAF-I* will be for the x-ray spectrum. *AXAF-I* is a smaller satellite than *HST*, and is in a higher, elliptical orbit. It has a fairly typical design for a medium-large satellite.

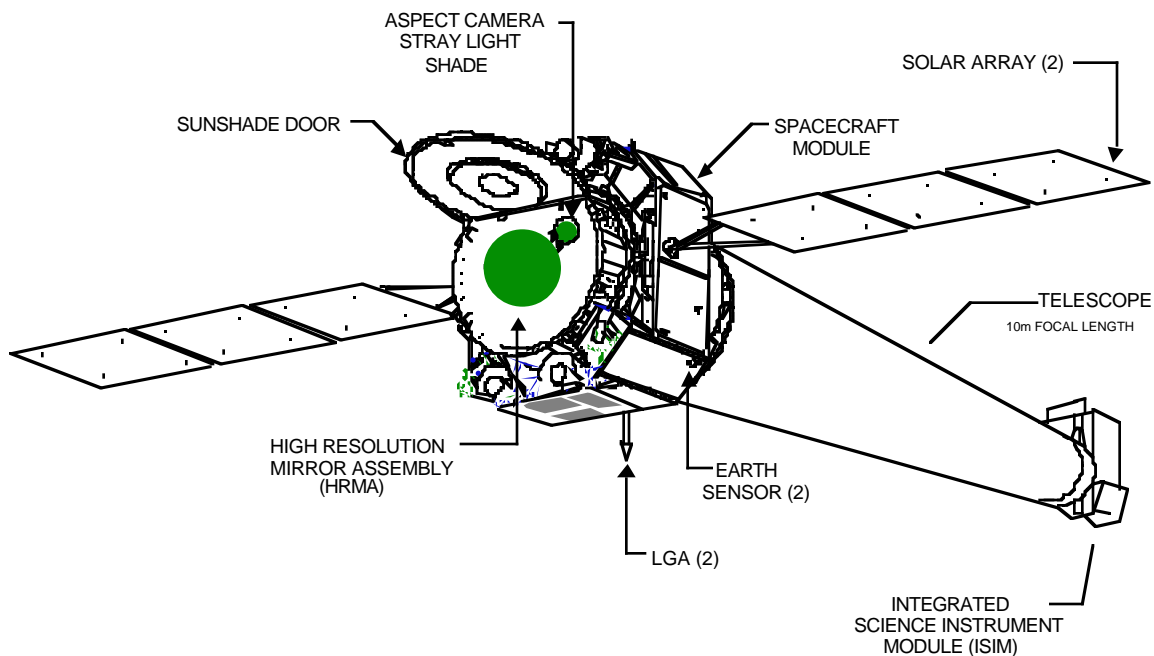


Figure 3. *AXAF-I*.

The electrical power system (EPS) consists of six solar array panels (deployed on two separate wings, each having three panels), three batteries, and the distribution system. The solar cells are arranged into a load section, three full-charge sections, and three trickle-charge sections. The load section consists of 180 strings of 70 cells each (30 strings per panel) which are diode coupled directly to the main bus. The nominal voltage at the main bus is 24.5 V. Each battery has 5 strings of 103 cells making up its full-charge section. The nominal voltage for recharging is 35 V. These cells are also diode coupled to the main bus from a tap at the 70th cell, so they can provide power to the load bus once the batteries are charged. Each battery also has a trickle-charge section, which is just like a full-charge string, but is always left connected to the battery.⁴

The batteries are sized to make it through a 2-h eclipse or safe mode operation with a maximum depth of discharge of 80 percent, assuming one battery has failed. Each battery consists of 22 series-connected nickel-cadmium (Ni-Cd) cells. Cell voltage can vary from 1.1 to 1.6 V, depending upon state of charge, so the battery can go from 24.2 to 35 V.⁵

Several power usage modes are defined so that peak power loading of the array can be kept within proper bounds. This is necessary because the high side of the battery is not connected to the bus during sunlight. There is a tap from the 16th cell, which is diode connected to the main bus to provide fault-clearing current if needed. Modes are also defined to allow tracking and control of the average battery power demands. The power modes are: battery charging peak power, maneuver peak power, warm-up peak power, nominal peak power, eclipse average power, and safe modes for sunlight and eclipse periods.⁶ The process of tracking peak power by controlling what loads can be operational is a clear instance of power system control by load management.

Skylab. *Skylab* (fig. 4) was America's first spacecraft with a significant utility aspect to the power system. The facility was launched on May 14, 1973. The power system consisted of two photovoltaic array systems, the Apollo telescope mount (ATM) charger battery regulator modules, and the airlock module (AM) power conditioning groups, and a distribution system.⁷ In addition, the command and service module (CSM) had its own EPS. The *Skylab* EPS design was evolutionary, resulting in a complex system. Due to some problems in launch, which included the loss of one of the airlock module/orbital workshop (AM/OWS) solar arrays and the necessity of a manual deployment of the other one, management of the power system was particularly intensive. Though inability to deploy the arrays had been considered as a contingency study, the partial availability that actually occurred required real-time decision making and power management planning.⁸

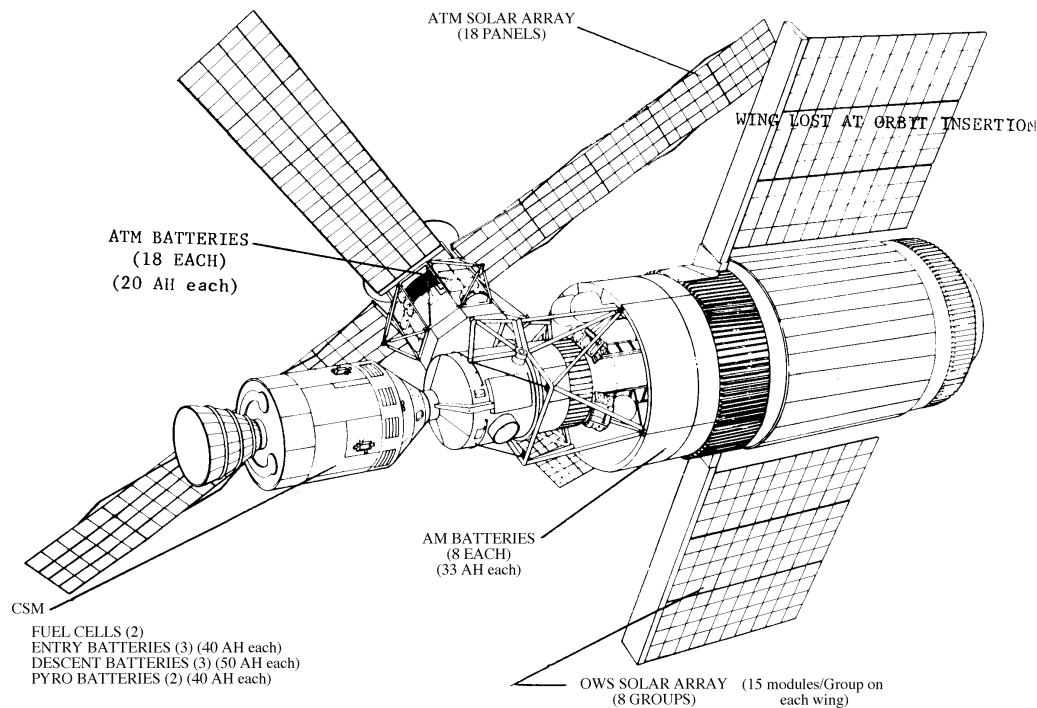


Figure 4. *Skylab*.

Skylab actually had two separate power systems, the ATM system and the AM/OWS system. The ATM solar arrays delivered about 12 kW of power when pointing directly at the Sun.⁹ The AM/OWS solar arrays were designed to provide about 10.5 kW. One of the two arrays was lost. After full deployment of the second, available daylight power from the array was between 6.5 and 7 kW.¹⁰ The two systems operated in parallel, so that after power conversion and taking into account orbital night and the losses associated with charging batteries, the power system provided about 8 kW for the combined system.¹¹ The two distribution systems were tied together, with a nominal voltage of 28 Vdc across the system.

Fuel cells powered the CSM, which transported the crew to and from *Skylab*. When docked, it acted as a third power system. However, as long as the fuel cells were active, it basically operated independently. When the fuel cells were turned off, the CSM became an additional load, averaging about 1 kW, with a peak of about 2.2 kW.¹²

Tools developed for prelaunch use included simplified power flow equations, energy balance equations, the *Skylab* electric power system analysis (SEPSA) computer program (which modeled

the power system, including attitude, position in orbit, and failure analysis capabilities¹³), a full set of functional schematics, and the load assumptions and power allocation documents. The load assumptions and power allocation documents included information for each load in the power system, such as power required for each operational mode over the possible input voltage range (28 Vdc nominal, but could range from 24 to 30 Vdc), peak load, bus connection, resistance of wiring from the bus to the component, operational constraints on the loads, and duration of operation for the different modes.¹⁴ Loads included life-support, housekeeping, experiment, instrumentation and communication, and attitude control systems.

During flight, all of the preflight tools were used. In addition, the electrical power system telemetry evaluation computer program was used to analyze the telemetry from the spacecraft to adjust parameters in the SEPSA model. Also, an EPS engineering data package was developed and regularly updated with general data and information needed for quick analysis of various situations.¹⁵

Almost all activities on *Skylab* were preplanned and coordinated in detail from the ground. Some loads, such as lighting, were crew adjustable. Loads like a portable vacuum cleaner and food warming trays varied in length of use. Power flow analysis was similar between *Skylab* and a small utility system, though clearly the dc case is simpler. Load scheduling was carefully constrained to assist in health management of the batteries and power conditioning equipment.

Mir. The *Mir* space station complex (fig. 5) base block was launched by the Soviet Union on February 19, 1986. The station was built up incrementally from the base block with the addition of the *Kvant*, *Kvant 2*, and *Kristall* modules. The *Spektr* module is planned for launch in May of 1995. Besides the modules, up to two other spacecraft are commonly docked to the complex. There have been as many as three. As long as the crew is on board, at least one *Soyuz-TM* vehicle remains docked. At crew change, there are typically two *Soyuz-TM*'s docked. Figure 5 shows one *Soyuz-TM* attached to the left end of the complex, and a *Progress-M* supply ship on the right end. When it arrives, the *Spektr* module will replace the *Kristall* module (pointing downward in the figure), and *Kristall* will be moved to the port where the *Soyuz-TM* is shown. The U.S. space shuttle will be docking to the port at the end of the *Kristall* module several times over the next few years.

The *Mir* power system is a combination of the systems of all the modules. The modules can be operated independently or tied together. Because of the incremental construction and aging of components, it is difficult to give a single system capacity. After the launch of *Spektr*, average power will be between 15 and 20 kW. Within each module, the power system is made up of power modules consisting of a solar array segment, a solar array regulator, a battery regulator, and a battery. The power modules are then connected in parallel between the solar array regulators and battery regulators to an adjustable bus-line unit. The voltage on this bus is filtered and converted to provide 28.5 ± 0.5 V to the distribution bus. The array and battery regulators are controlled to assure equal loading across the power modules, and also allows "normalizing cycles" to keep the batteries healthy. On *Mir*, normalizing means fully charging each battery in two consecutive cycles and doing a complete discharge and recharge of each battery at least twice a month.¹⁶

For typical operation, power use is scheduled, but not very closely. System health is monitored, and schedules are adjusted if necessary. Batteries are not required to be fully charged at the end of each orbit. Cosmonauts are free to use many powered items without communication with controllers on the ground. If battery charge drops too low, automatic load shedding occurs. *Mir* really does demonstrate utility style operation.

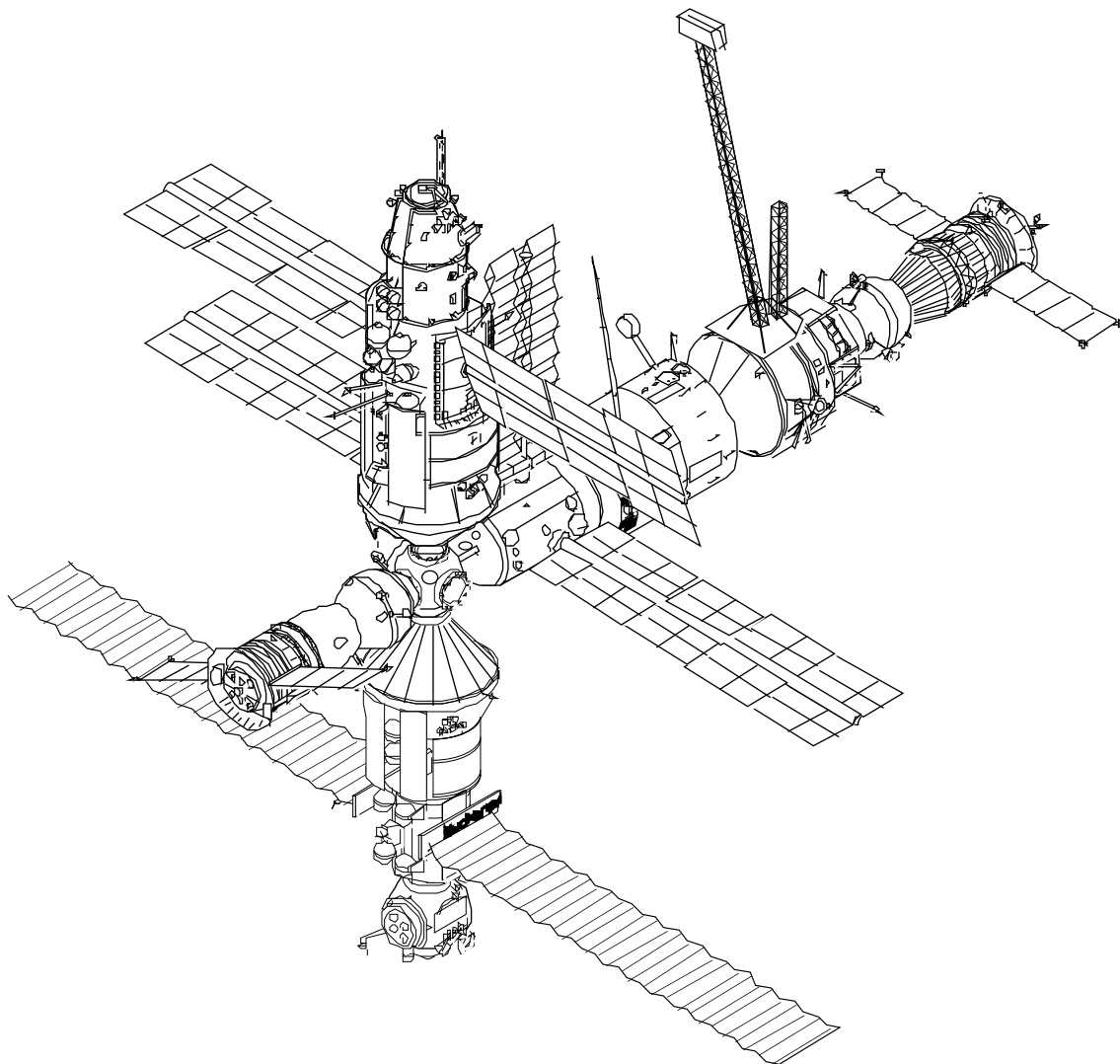


Figure 5. *Mir*.

International Space Station Alpha (ISSA). *ISSA* (fig. 6) is a major space facility intended for long-term use as a laboratory, observatory, and commercial facility. It is a joint effort of most space-faring nations. First element launch is planned for 1997.

ISSA will be built up over about 5 years, starting with a Russian-supplied core module similar to the *Mir* central module. Like *Mir*, the system will be built up modularly. The first module includes a photovoltaic system of about 2.7 kW. After the addition of a U.S. node, a Russian service module will be added with a power system similar to the first. After several more modules are added, the first of the large U.S. array segments are added in a temporary configuration, which adds about 15 kW of capability. A Russian tower is added after that, which holds six arrays when fully populated (top center in fig. 6). The figure shows the fully assembled station, with a combined power system of over 100 kW.

The following is a description of the power system from the *ISSA* Technical Data Book, available on the internet at <http://issa-www.jsc.nasa.gov/ss/techdata/techdata.html>:

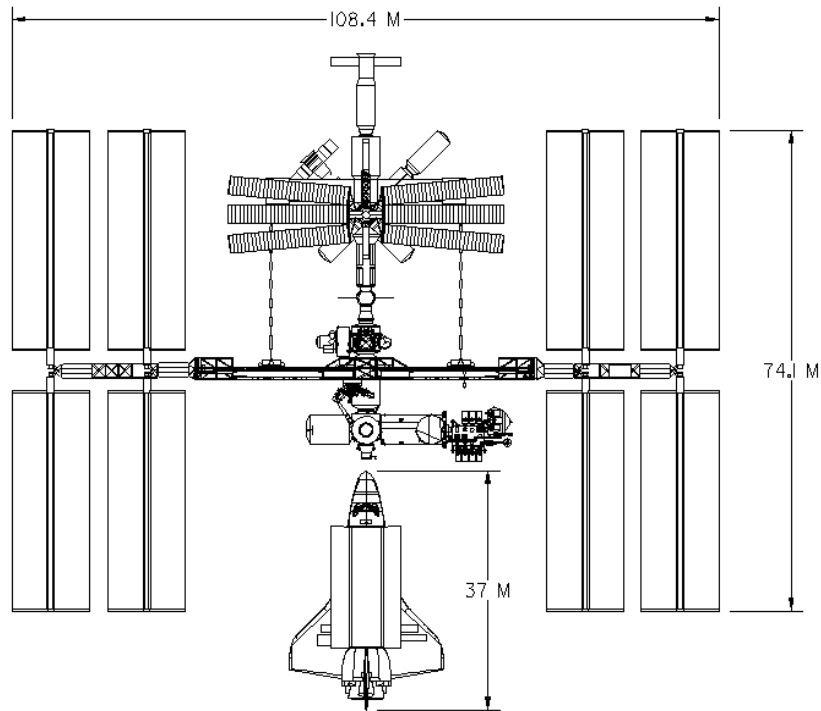


Figure 6. ISSA.

“The function of the Electrical Power System (EPS) is to generate power, store energy, and distribute power to the Station for housekeeping loads and payloads. The EPS provides on-demand and scheduled power to the Station. The EPS generates primary power which is distributed from the power sources to a central switching location on the Integrated Truss Segment (ITS) S0. Primary power is then routed externally along the ITS and internally to the pressurized modules, and later converted to 120 Vdc secondary power. The secondary is distributed via additional switch gear to the electric power consuming equipment of Station core subsystems, utilities, and payloads.

The EPS is comprised of power sources and distributed hardware. The main sources of primary power for the Station are the (4) four U.S. photovoltaic (PV) Modules and the Russian Power Mast. Each U.S. PV Module is composed of these major components: Solar Array Wings (SAW) (panels), Sequential Shunt Units (SSU), Beta Gimbal Assemblies (BGA), PV Radiator, and the Integrated Equipment Assembly (IEA) which contains batteries, Battery Charge / Discharge Units (BCDU), Direct Current Switching Units (DCSU), DC-to-DC Converter Units (DDCU), Pump and Flow Control Assembly (PFCA), and Photovoltaic Controller Units (PVCU). EPS distribution hardware includes Solar Alpha Rotary Joints (SARJ), Main Bus Switching Units (MBSU), DDCUs, and Remote Power Controller Modules (RPCM), which are contained within Secondary Power Distribution Assemblies (SPDA) and Remote Power Distribution Assemblies (RPDA).”¹⁷

The methods that will be used to manage the power system on *ISSA* have not been firmly established. It will be the largest space power system ever flown, and the most complex. Probably the Russian and American sections will be operated separately from the respective control centers,

with significant communication between the two centers. The traditional American method of managing space power, as evidenced by *Skylab* and current shuttle missions, involves intense scheduling and tight control of resources. The Russian system, as demonstrated on *Mir*, involves a lighter control, more like that used by terrestrial utilities. The continuous nature of *ISSA* operation will undoubtedly cause the American operators to also move toward more of a utility orientation. The next section of this report will examine the differences between space and terrestrial power.

DIFFERENCES BETWEEN SPACE AND TERRESTRIAL POWER

A century's time and practice have developed a whole suite of techniques for dealing with generating and distributing power here on Earth. Some of these "old" ways of doing business work as well in space as on Earth, some do not work at all, and some may work, but not as well as alternatives. This section highlights some of the differences in environment and practice.

Scale

Terrestrial utility systems are much larger than space power systems. The largest power system for an American satellite was *Skylab*'s 8-kW system.¹⁸ The Russian *Mir* complex totals less than 28-kW capacity.¹⁹ The *ISSA* will grow to a total capacity of about 110 kW.^{20*} Compare this to the typical output of a hydroelectric dam (tens to hundreds of megawatts) or steam plant (thousands of megawatts), and you can see how capacity differs. Compare this to the capacity of the North American power grid[†] and it is dwarfed indeed.

Cost

On the other hand, the cost of supplying and distributing power on orbit is much, much higher cost per kW than on Earth. The total cost of the power system of the *ISSA* is hard to calculate, but will be in the billions of dollars. The largest cost for the components in space is transportation. Both weight and volume are extremely expensive. On Earth, it might be wise to go with a marginally cheaper component, even if it were twice the weight and volume of the comparable component. In space, on the other hand, a 50-percent reduction in weight and volume would almost always be worth spending 10 times as much on the component. Dependability is also more important in space, since the cost of making a replacement is usually many times more expensive than the component.

Sources

Terrestrial power systems use economy of scale in the production of power. Most generation involves large turbines, driven by either nuclear- or coal-fueled steam, or by flowing water. The mechanical systems have been sized for maximum efficiency and stability, and the resulting size is large: typically several tons. Space power systems typically use photovoltaic solar arrays, coupled with batteries for energy storage while the spacecraft is in shadow.

* Of this, about 80 kW is from the U.S. power system, the rest is from the Russian system.

† Estimates for 1993 capacity for the U.S. and Canada, excluding Alaska, is about 800,000 MW, with a peak use (summer peak) of about 600,000 MW.

Transmission

Because of the economy of scale on Earth, it is most efficient to generate the power at large, central locations and distribute it, often over great distances, to the users. By the nature of large-scale power production, generation and use are seldom collocated, except for some industrial users. Few large cities care to have a large power plant downtown. In space, generation and use are normally very closely connected. Thus, techniques for efficient transmission on Earth, such as extremely high voltage transmission lines, are not required in space. There, need is a for lightweight transmission without major loss, but it is over such short distances that transmission is practically subsumed by distribution.

The need for high voltage transmission to minimize loss over long distances makes ac the best choice for terrestrial power supply. Alternating current generators are simpler to design and build, and transformers can be used to raise voltage for transmission and lower it for distribution with little loss. Electric motor loads can be simpler, too. Switching is also easier with ac because the circuit can be broken when current is reversing direction (at a zero crossing).

In space the choice is less clear. Photovoltaic arrays and batteries are both dc components. A smaller proportion of space loads are rotating machines. Direct current-direct current converters (which change the dc voltage), while still heavier and more complex than a transformer to make the same change for similar ac voltages, are much smaller and more efficient than they once were. Switching is still a more difficult task with dc, but solid-state switching components have mitigated the problem. The components required to invert the dc source signals to ac, and to convert back at the loads, is generally more expensive in terms of complexity and weight, than the extra copper and the larger components necessary for dc. As a result, most space power systems are dc throughout.

Distribution

Distribution is rather similar for space and terrestrial cases. In both situations, a desire for redundant interconnection is balanced with the desire to avoid cost.

Loads

On Earth, the presence or absence of loads is up to customers. The providers adapt source availability to fit the need. Power system managers can use statistical methods to predict what load will be, but they have little say in determining the load. In space, power is among the tightest resources. The total energy budget is fixed by the original power system design. The problem of space power management, then, is not to adjust source to meet to load, but to adjust the load to get as much use out of the most important loads as possible. This is load management.

Operations and Planning

Today, both terrestrial and space power systems are controlled from computer-filled control rooms remote from the hardware, at least for day-to-day operations. Controllers of terrestrial systems do have some advantages not shared by controllers of space systems, though. A key advantage is the interconnectedness of the terrestrial power grid. All but a few isolated areas (such as Abu Dhabi²¹) have connections to other utilities. These interconnections provide greater stability

and security for the overall power grid, since, for instance, the loss of even an extremely large generating unit is only a small percentage of the whole grid's supply, though it might be a major component of a local utility. Because of the wide geographic distribution, it is very unlikely that any catastrophe, other than a major war, would affect the whole system at the same time. Though *ISSA*, *Mir*, and *Skylab* all had separate power systems working together, the geographic distribution is not there, and the loss of a single solar array is a significant part of total generation for all of these spacecraft.

CONCLUSIONS

The brief history of space power presented in this report shows the increasing complexity of space power systems and gives some insight into approaches for operating such systems. The comparison of space power systems with terrestrial utilities shows some of the differences between the systems. As space systems continue to grow in size and complexity, the methods of operation used will become more like those used on Earth. Some terrestrial techniques will be applicable and appropriate, others will not. The attempt of this report was to present some of the issues involved to serve as a basis for determining appropriate transitions of technology from the terrestrial realm to space applications.

REFERENCES

1. Government Data Publications, "Satellite Probe Volume and Directory," Washington, 1963, pp. 1–3.
2. Baalke, R.: "Voyager Mission Update, March 1, 1995." Jet Propulsion Laboratory, Public Information Office Release, March 1, 1995.
3. Wilson, A., ed.: "Interavia Space Directory 1990–91." Jane's Information Group, pp. 91–94.
4. Crum, W.M.: "AXAF-I System and Subsystem Technical Analyses and Models: Electrical Power System Model." TRW Report Number 52100.300.021 for NAS8-37710 DPD692 SE11q, October 11, 1994, pp. 4–5.
5. *Ibid.*, p. 3.
6. *Ibid.*, p. 4–5.
7. Chubb, W.B., ed.: "Skylab Reactivation Mission Report." NASA TM-78267, March 1980.
8. Woosley, A.P.: "MSFC Skylab Electrical Power Systems Mission Evaluation." NASA TMX-64818, June 1974, pp 31–33.
9. *Ibid.*, p. 279.
10. *Ibid.*, p. 217.
11. *Ibid.*, p. 203.
12. *Ibid.*, p. 201.
13. *Ibid.*, p. 373.
14. *Ibid.*, pp. 26–30.
15. *Ibid.*, p. 31.
16. Horunov, V. P.: "Orbital Station 'Mir' Power Supply System." *Mir* Space Station Symposium "A Technical Overview," July 27–28, 1993.
17. Electrical Power System (EPS) on Flight 19A, International Space Station Technical Data Book, <http://issa-www.jsc.nasa.gov/ss/techdata/EPS/19A.html>, April 25, 1995.
18. Woosley, A. P.: "MSFC Skylab Electrical Power Systems Mission Evaluation." NASA TMX-64818, June 1974, p. 203.
19. Portree, David S.F.: "Mir Hardware Heritage." JSC 26770, October 1994, p. 102.
20. Huckins, E., and Ahlf, P.: "Space Station Power Requirements and Issues."

21. El-Banhawy, M.H., and Al-Gobaisi, B.M.K.: "Development of Optimal Emergency Control Strategies for Abu Dhabi Power System." IEE International Conference on Power System Monitoring and Control, June 1991, pp. 50–55.